REBAL '92 - A COOPERATIVE RADIATION AND ENERGY BALANCE FIELD STUDY FOR IMAGERY AND E.M. PROPAGATION

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ABSTRACT

The surface energy balance affects the structure of temperature and humidity gradients in the atmospheric surface layer. Temperature and moisture gradients are needed to estimate the intensity of optical turbulence along a given path, but models of these relationships are not adequately validated for imagery and electromagnetic propagation applications. A field study entitled 'Radiation Energy Balance Experiment for Imagery and E.M. Propagation' (REBAL '92) was conducted by the U.S. Army Atmospheric Sciences Laboratory (ASL) and the USDA Agricultural Research Service (ARS), at Bushland, Texas, in May and July 1992. We collected diurnal radiation, evaporation (directly measured by weighing lysimeters), 5-level micro-meteorological profiles of wind speed, air temperature, and relative humidity, soil temperature and water content, soil heat flux, optical turbulence (scintillometer), and near- and far-field infrared imager data over wet and dry bare soil under clear and cloudy sky conditions. Initial model tests indicate excellent agreement between measured and modeled values of the optical turbulence structure parameter, C_n^2, for one day. Future model evaluation will extend over the wide range of conditions encountered during the field study.

1. INTRODUCTION

Understanding surface radiation/energy balance processes is important for estimating evaporation rates and understanding surface-layer temperature gradient structure. Both Department of Defense (DoD) and United States Department of Agriculture (USDA) are interested in the development of numerically efficient methods or models to describe the partitioning of the net radiative flux into sensible, latent, and soil heat fluxes and the impact of surface fluxes on atmospheric profile structure. To make efficient use of limited fiscal and personnel resources, an integrated, multi-agency effort was initiated to improve current models. This cooperative DoD-USDA research-oriented field program, the Radiation and Energy Balance Experiment (REBAL '92) was organized by the US Army Atmospheric Sciences Laboratory (ASL) and the USDA Agricultural Research Service (ARS), Conservation and Production Research Lab (CPRL). REBAL '92 was conducted at Bushland, Texas at the ARS/CPRL experimental site in May and July 1992. The site was chosen due to the presence of four large weighing lysimeters. Direct measurements of latent (evaporative) heat flux were lacking in several previous micro-meteorological field tests.

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REBAL '92 was initiated to improve the knowledge on radiation/energy balance partitioning and to characterize surface layer micro-meteorological processes over wet and dry, soil surfaces. The project's goals were:

1. To collect radiation, evaporation, micro-meteorological profile, and optical turbulence scintillometer data over wet and dry bare soil, under clear and cloud covered skies. In addition, infrared imager data in a near field/far field configuration was collected simultaneously to characterize the effects of optical turbulence on a thermal bar pattern (Watkins et al., 1991a) to determine the temporal turbulent distortions of the imaged target.

2. To evaluate and refine two energy balance models (Evett et al., 1991; Rachele and Tunick, 1992a).

The effects of the atmosphere are basic to the performance of advanced, high resolution systems and sensors, including lasers and imaging systems. The US Army interests in the REBAL '92 field study focus on atmospheric effects on electromagnetic propagation, imagery (including infrared), and target recognition. These research efforts are influenced by the phenomenon referred to as optical turbulence. Optical turbulence is a function of the character and structure of temperature and moisture gradients in the atmospheric surface layer (Tunick and Rachele, 1991). Reasonable estimations of the energy balance fluxes are required to predict the character and intensity of the optical turbulence. Scintillometer data are critical for verification and evaluation of the energy balance models and electromagnetic propagation models.

The USDA-ARS research interests in the REBAL '92 field study focus on improved knowledge of the energy balance fluxes, especially the evaporative or latent heat flux, for applications such as predicting crop water use and to improve irrigation scheduling and crop growth models.

The purpose of this paper is to present an overview of the REBAL '92 experiment including project objectives and goals, research interests, site description, experimental layout, methodology, instrumentation, and preliminary results from the test.

2. THEORY

Carson (1987) defined the energy flux balance at the soil surface as

$$R_n = H + L'E + G \tag{1}$$

where R_n is the net radiative flux, H is the sensible heat flux, L'E is latent heat flux with L' as the latent heat of vaporization [2.45×10^6 J/kg] and E as the evaporation rate in kg m^{-2} s^{-1}, and G is soil heat flux; units are in W/m^2. During REBAL '92, R_n, E, and G were measured directly (net radiometers, lysimeters, and soil heat flux plates/thermocouples, respectively) while H was computed as the residual. Carson (1987) also defined the net radiative flux at the soil surface as the sum of the net short-wave radiative flux and the net long-wave radiative flux as

$$R_n = R_s - R_{sr} + R_{li} - R_{lu} \tag{2}$$

where R_s is incident solar radiation, R_{sr} is reflected solar radiation, R_{li} is sky emitted long-wave radiation, R_{lu} is ground emitted long-wave radiation, and the units are in W/m^2. The short-wave reflection, albedo, is computed as R_{sr}/R_s. The effects of surface soil water content, surface roughness, and solar elevation angle on albedo is part of the REBAL '92 study along with the characterization of the net long-wave radiative flux as affected by different cloud type, amount of cloud cover, and surface soil water content.

A key element of the REBAL '92 field study is the application of radiation/energy balance measurement and modeling to imagery and electromagnetic propagation as affected by optical turbulence. The character and intensity of optical turbulence is represented by C_n^2, the optical turbulence structure parameter. Given reasonable estimations of the energy balance fluxes, one can determine the relative magnitude of C_n^2 (Rachele and Tunick, 1992b). For damp unstable conditions, the optical turbulence structure parameter can be expressed as

$$C_n^2 = A'\theta^{\bullet 2} + B'\theta^\bullet q^\bullet + C'q^{\bullet 2} \tag{3}$$

where

$$A' = b\,(2.897 \times 10^{-8})\,\frac{p^2}{T^4}\,k^{-2/3}z^{-2/3}\left(1 - 15\frac{z}{L}\right)^{-1}\omega \tag{4}$$

$$B' = b\,(1.444 \times 10^{-8})\,\frac{p^2}{T^3}\,k^{-2/3}z^{-2/3}\left(1 - 15\frac{z}{L}\right)^{-1}\omega \tag{5}$$

$$C' = b\,(1.801 \times 10^{-9})\,\frac{p^2}{T^2}\,k^{-2/3}z^{-2/3}\left(1 - 15\frac{z}{L}\right)^{-1}\omega \tag{6}$$

and where

$$\omega = \left\{ \frac{\left(1 - 15\frac{z}{L}\right)^{1/2}}{\left[\left(1 - 15\frac{z}{L}\right)^{-1/4} - \frac{z}{L}\right]^{1/3}} \right\}$$

where C_n^2 is the optical turbulence structure parameter in $m^{-2/3}$, b is the Obukhov-Corrsin constant [3.2], k is von Karman's constant [0.4], z is height in m, L is the Obukhov scaling length in m, T is the air temperature at height z in °K, p is barometric pressure in kPa, $\theta^\bullet$ is the scaling constant for temperature, and $q^\bullet$ is the scaling constant for specific humidity. The scaling constants for temperature and specific humidity can be expressed in terms of sensible heat and latent heat fluxes as

$$\theta^\bullet = \frac{-H}{C_p\rho u^\bullet} \qquad q^\bullet = \frac{-L'E}{L'\rho u^\bullet} \tag{7}$$

where C_p is the specific heat [1003 J kg^{-1} $°C^{-1}$], ρ is the density of moist air [1.0 kg m^{-3}], and $u^\bullet$ is the surface friction velocity in m/s. Finally, the optical turbulence structure parameter can be expressed in terms of sensible heat and latent heat fluxes as

$$C_n^2 = A'\left(\frac{(-H)^2}{C_p^2\rho^2 u^{\bullet 2}}\right) + B'\left(\frac{(-H)\,(-L'E)}{C_p L'\rho^2 u^{\bullet 2}}\right) + C'\left(\frac{(-L'E)^2}{L'^2\rho^2 u^{\bullet 2}}\right) \tag{8}$$

The surface friction velocity, $u^\bullet$, can be determined iteratively given the expression for the Obukhov scaling length $L = \dfrac{-u^{\bullet 3}C_p\rho\theta}{kgH}$, and the similarity profile function for the mean horizontal wind speed. This procedure is

167

discussed in detail in Rachele and Tunick, 1992a.

3. SITE DESCRIPTION

The test site at ARS/CPRL in Bushland, Texas (35°N Lat, 102°W Long, 1,170 m elevation MSL) is approximately 16 km due west of Amarillo, Texas. Four weighing lysimeters are located in a 20 ha field with each lysimeter centered in a 4.6 ha sub-field (215 m by 215 m). The topography is relatively level with a slope to the SE of less than 0.15%. There are no vertical obstructions near the field, and over 1,000 m of cropped or fallow agricultural fields provided unobstructed upwind fetch in the predominant summer wind direction (SSW).

The test area (the NW and SW sub-field) was a tilled, bare soil (Pullman clay loam) expanse approximately 215 m by 430 m, containing two of the four weighing lysimeters (fig. 1). Irrigated and dryland wheat fields (NE and SE lysimeter fields, respectively) were directly east of the test area. Prior to the July REBAL '92 study period, these wheat fields, as well as dryland wheat to the south of the test area, were harvested leaving a short stubble residue.
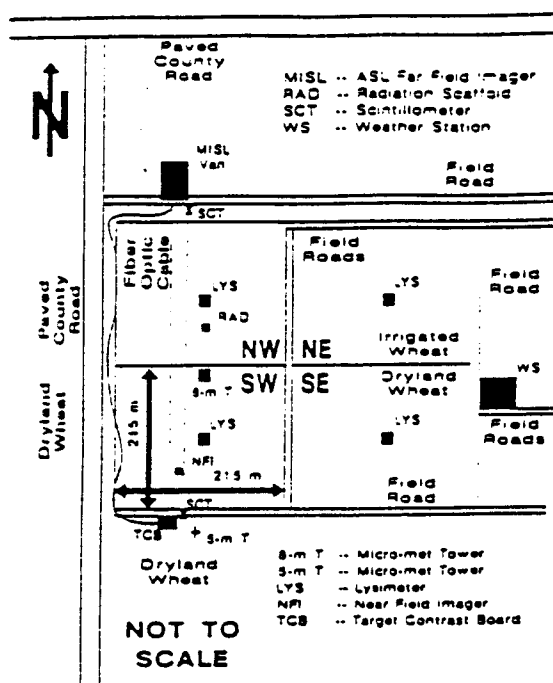

Figure 1. The experimental test area.

4. EXPERIMENTAL LAYOUT AND METHODOLOGY

Micro-meteorological profile data (wind speed, air temperature, and relative humidity) were measured with sensors mounted on an 8-m tower centered in the test area (fig. 1) at 0.5-, 1-, 2-, 4-, and 8-m elevations. Six radiometers and one infrared thermometer (IRT) measured the radiation balance components at a site approximately 80 m north of the profile tower (and about 15 m south of the NW lysimeter). Wind speed, wind direction, air temperature, and relative humidity were also measured at the radiation measurement site at the 2-m elevation. Table 1 contains a list of the instruments deployed in the REBAL '92 experiment.

168

The ASL Mobile Imaging and Spectroscopy Laboratory (MISL) trailer was located at the north end of the test area. The trailer contained the imaging equipment, cameras and recorders. A 0.94µm scintillometer source module was mounted 2 m above ground on a tripod located adjacent to the MISL trailer. The imaging cameras and the scintillometer were aligned and focused down-field (i.e., to the south) over a path of approximately 450 m.

The receiver module of the scintillometer, the target board (a thermal bar pattern), a small source van (a vehicular target), and an auxiliary 5-m micro-meteorological tower were located at the south end of the test area. Instrumentation on the auxiliary micro-meteorological tower measured 2- and 5-m elevation wind speed and direction, air temperature, and relative humidity and solar radiation, barometric pressure, soil temperature (100 mm depth), and visibility near the target board to provide site specific data for the target contrast board environment at a frequency synchronized with the imagery data.

4.1 DATA COLLECTION SUMMARY

Micro-meteorological profile data and radiation/energy balance data were collected in May 1992 (DOY 132 - DOY 141) and in July 1992 (DOY 190 -DOY 196). Scintillometer and infrared image data were collected during selected periods (Table 2) within that time frame. The field was sprinkler irrigated once on DOY 132 while significant rainfall events (i.e., more than trace rainfall) occurred on DOY 136, DOY 141, DOY 191, and DOY 192. Table 2 summarizes weather during the data collection periods. Two daily radiosonde observations and hourly cloud observations were recorded and four daily surface weather charts were provided during both data collection periods by the National Oceanographic and Atmospheric Administration (NOAA), National Weather Service (NWS) Office in Amarillo, Texas (about 35 km east of the field site).

4.2 LYSIMETER MEASUREMENTS

The lysimeter is an intact soil monolith (3 m by 3 m square and 2.4 m deep) that can be weighed to a mass equivalent of 0.02 to 0.05 mm of water which corresponds to an hourly evaporative flux of approximately 14 to 34 W/m^2 (Dusek et al., 1987, Marek et al., 1988, Steiner et al., 1991). The lysimeters directly measured the water mass contained in the soil monolith. The change in this mass in a given time interval is the evaporation rate. The water mass was measured at 0.5-hz frequency, averaged for 5 min periods, the difference between successive 5-min periods was averaged for 15 min periods, and these 15-min evaporation rates were smoothed using a 3-point equally weighted running mean. The latent heat flux (in W/m^2) was computed as the product of the evaporation rate (kg m^{-2} s^{-1}) and the latent heat of vaporization (J/kg). At each lysimeter, net radiation, reflected solar radiation, surface temperature, soil heat flux (50 mm depth), soil temperature (averaged for the 10-mm and 40-mm depths), and wind speed profile (0.8-, 1.3-, 1.8-, and 2.3-m elevations) and dry- and wet-bulb temperatures (1.3- and 2.3-m elevations) were measured at 0.17 hz and averaged for 15 min. Soil heat flux was corrected calorimetrically to the surface using the change in soil temperature above the plates and the soil heat capacity. Within the NW lysimeter, two arrays of Time Domain Reflectometry probes measured soil water contents at 20 and 40 mm at 30-min intervals. This soil water content was used to estimate the surface soil heat capacity in both lysimeters.

169

TABLE 1. List of instruments[1] deployed in REBAL '92.

Parameter/Equipment	Manufacturer/Model	Deployment
8-m Tower		
Air Temperature/Relative Humidity (aspirated)	Rotronics HT225R/ SMP410012	0.5, 1, 2, 4, and 8 m
Air Temperature (non-aspirated)	Climatronics 100093-3	same
Wind Speed	R.M. Young 12102	same
Wind Direction	R.M. Young 12302	8 m
Radiation Scaffold		
Incident Solar Radiation	Eppley PSP	1 m
Reflected Solar Radiation	Eppley 8-48	1 m (inverted)
Sky Long-Wave Radiation	Eppley PIR	1 m
Emitted Ground Radiation	Eppley PIR	1 m (inverted)
Net Radiation	REBS Q*6	1 m
Total Hemispherical Radiation	REBS THRDS5	1 m
Surface Temperature	Everest 4000	1 m (nadir; 60° fov)
Air Temperature/Relative Humidity (non-aspirated)	Rotronics HT225R/ SMP 41002	2 m
Wind Speed	R.M. Young 12102	2 m
Wind Direction	R.M. Young 12302	2 m
Lysimeter		
Reflected Solar Radiation	Eppley 8-48	1 m (inverted)
Net Radiation	REBS Q*6	1 m
Surface Temperature	Everest 4000	1 m (nadir; 60° fov)
Soil Heat Flux	REBS TH-1	50 mm
Soil Temperature	Thermocouples (Cu-Co)	10 and 40 mm (averaged)
Soil Water	TDR (3-prong probes)/ARS-CPRL design	20 and 40 mm (averaged)
Wind Speed	Met One 024	0.8, 1.3, 1.8, and 2.3 m
Dry- and Wet-Bulb Temp. (psychrometers)	Thermocouples	1.3 and 2.3 m
Lysimeter Mass	Cardinal FS-7 Scale/Alphatron SL50 load cell	
Optical Turbulence/E.M. Imaging		
Scintillometer	Lockheed Engr. & Mgmt. IV-L	N to S; 450 m path; 2 m
Visible Cameras/Lens	Sony NTSC DX 102s 10 power zoom lens	N to S; 50 and 450 m paths; 2 m
Infrared Imagers	Inframetrics 610s/ 10 power lens	N to S; 50 and 450 m paths; 2 m
Target Contrast Board	US Army ASL	S end of field
Image Recording	Analog tape	N end of field (MISL van)
Image Registration	Recognition Concepts Inc.	N end of field (MISL van)
Target Met Tower		
Solar Radiation	Qualimetrics 3120	2 m
Air Temperature/Relative Humidity (non-aspirated)	Campbell Scientific 207	2 m and 5 m
Soil Temperature	Yellow Springs Instr. 703	100 mm
Barometric Pressure	Intellisensor AIR-DB	2 m
Wind Speed/Direction	R.M. Young 05103	2 and 5 m
Visibility	HSS VF-500-100.	3 m

[1] The use of corporation or company names with regard to instrumentation and equipment used does not constitute an endorsement by either the US Army or the USDA-ARS.

TABLE 2. Summary of weather conditions during REBAL '92 in May and July, 1992, Bushland, Texas.

Day of Year	T_{max}[1]	T_{min}[1]	T_{dew}[1]	Daily Solar Radiation	Daily Mean 2-m Wind Speed	Rain or (Irrigation)
	°C	°C	°C	MJ/m²	m/s	mm
132[2]	26.4	5.4	2.3	28.3	2.4	(32.00)
133[2]	31.5	9.0	2.0	27.1	3.0	0.00
134[2]	27.9	12.4	8.5	22.9	4.4	0.00
135	30.1	11.8	7.4	26.6	3.8	0.00
136	29.8	13.4	8.2	25.2	4.1	3.05
137	26.1	11.9	7.5	25.9	4.7	0.00
138	25.0	10.6	8.3	26.0	4.8	0.00
139[2]	25.3	9.6	7.9	26.9	2.5	0.00
140[2]	26.5	11.7	8.2	25.5	3.1	0.00
141[2]	24.3	12.2	10.2	17.4	4.2	15.24
190[2]	33.9	17.7	9.2	28.7	5.3	0.00
191[2]	33.5	15.9	11.7	28.0	5.3	27.94
192[2]	30.1	17.6	15.4	24.3	4.2	6.86
193[2]	30.5	17.2	15.2	26.8	6.8	0.00
194	32.1	19.0	13.5	27.9	7.2	0.00
195[2]	31.4	17.0	12.8	25.9	3.7	0.00
196[2]	30.5	14.5	12.9	26.8	2.7	0.00
197	34.3	18.7	13.1	26.8	4.5	0.25

[1] T_{max}, T_{min}, and T_{dew} are daily maximum, minimum, and mean dew point temperatures, respectively, measured from a standard weather shelter at 1.5 m height about 220 m east of the REBAL '92 field.

[2] Days when scintillometer and infrared image data were collected.

4.3 TARGET CONTRAST CHARACTERIZER

The Target Contrast Characterizer (TCC) compares infrared scene features collected simultaneously from an imager located near the target and from an optically-matched imager located far from the target. The imagers share a common line of sight with the target, and the "near-field" images are transmitted over a video fiber-optics data cable to the far-field position for processing and recording. The "far-field" imager is coupled to a telescope of sufficient power to provide "far-field" images of the same dimensional field of view in the target plane as the "near-field" images. Pixel-to-pixel frame

171

registration, critical to the success of this technique, is obtained through the use of a Recognition Concepts, Inc. real-time image processing system. The TCC quantifies the effect of optical turbulence on imagery by measuring the atmospheric modulation transfer function (AMTF). A large area target board (1.78 m by 1.78 m) with uniform surface temperature was used to measure the AMTF. A bar-pattern mask placed in front of the target board produced sharp hot-to-cold bar radiance transitions needed for measuring the AMTF. Video signals from visible, 3- to 5-μm, and 8- to 12-μm imagers were recorded on VHS video tape. For the REBAL '92 study, the "near-field" imager was placed 48 m from the target board and the "far-field" imager, coupled to a 10-power telescope, was placed approximately 450 m from the target board. The TCC is conceptually depicted in figure 2 and described in detail in Watkins et al. (1991b).
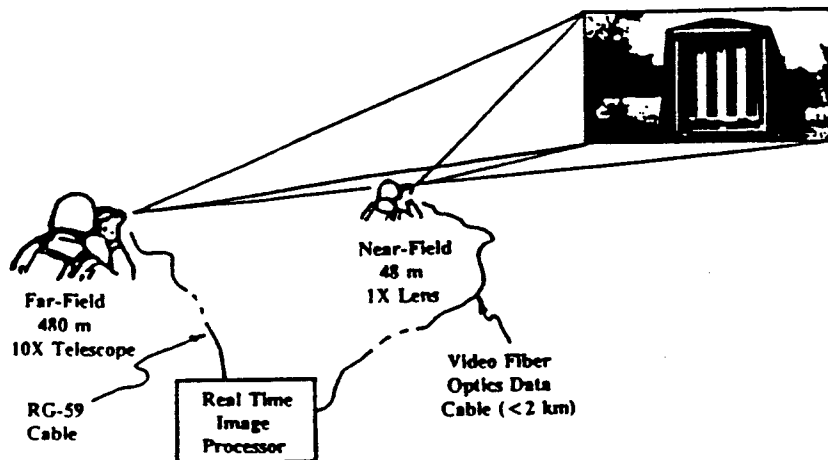
Figure 2. Conceptual use of the Target Contrast Characterizer.

4.4 SCINTILLOMETER MEASUREMENTS

A scintillometer is a ground-based, remote-sensing instrument designed to measure optical turbulence intensity along a line-of-sight path established between a transmitter and a downrange receiver. Scintillometer operation is based on the principle that scintillations or light intensity variations occur as atmospheric density discontinuities create refraction effects in light propagating along a path (Clifford et al., 1974). The optical turbulence structure parameter, C_n^2, is related to the intensity of these refraction effects.

5. PRELIMINARY RESULTS

Energy balance and optical turbulence structure parameter measurements on DOY 134, which was 1-1/2 days after irrigation of the test area in May (Table 2), will be used to illustrate a portion of the data collected during REBAL '92. Figures 3 and 4 show the measured wind speed, temperature and dew point temperature at 2 m for DOY 134. Wind speeds ranged from 2-6 m/s increasing somewhat by 2200 CST. Air temperature at 2 m was between 12.0 and 28.0 °C. Figure 5 illustrates the observed energy balance components on DOY 134. Figure 6 illustrates good agreement between C_n^2 measured by a scintillometer and calculated from the observed sensible and latent heat flux data (Eqn. 8). The comparison shows exceptional agreement considering the complexity of the

problem. Therefore, given reasonable values for the energy flux components, whether measured or modeled, the character of the optical turbulence represented by the optical turbulence structure parameter, C_n^2, can be accurately determined.
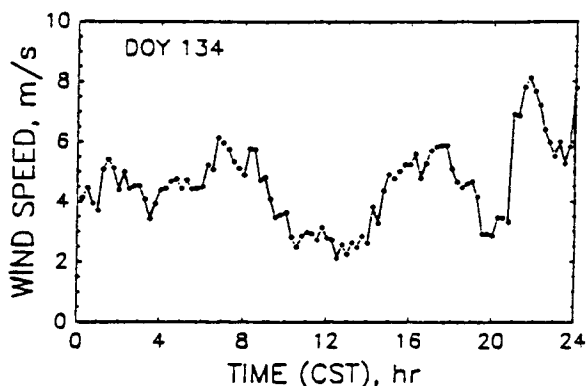

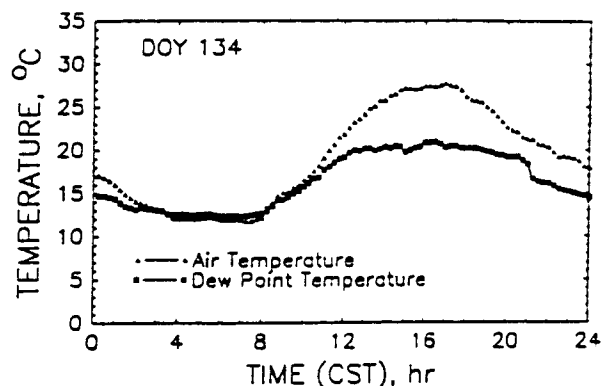Figure 3. Wind speed a 2-m elevation during DOY-134 above bare soil.

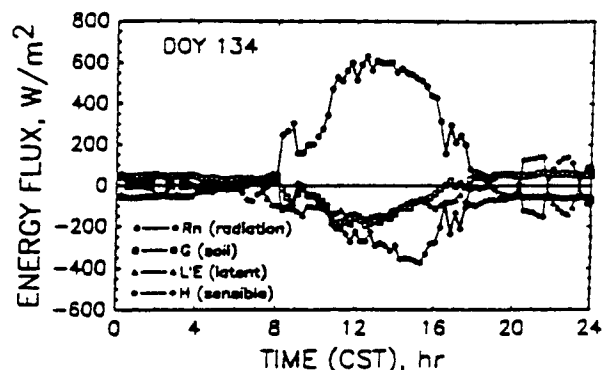Figure 4. Air temperature and dew point temperature at 2-m elevation during DOY-134 above bare soil.
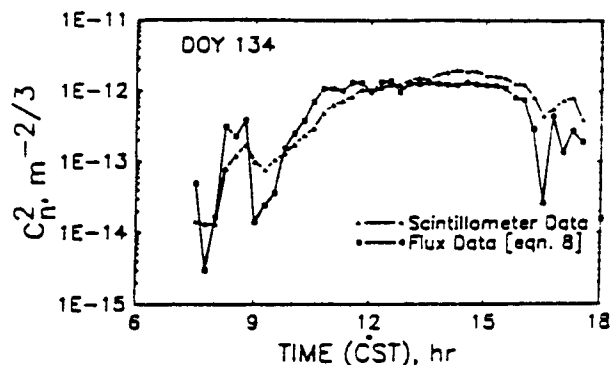

Figure 5. Radiation/Energy Balance Fluxes during DOY-134 at Bushland, TX for bare soil.

Figure 6. Measured and modeled C_n^2 for DOY-134 at Bushland, TX for bare soil

6. SUMMARY

A field study entitled 'Radiation and Energy Balance Experiment for Imagery and E.M. Propagation' (REBAL '92) was conducted cooperatively by the US Army ASL and the USDA-ARS/CPRL at Bushland, Texas in May and July 1992. A unique set of radiation/energy balance, micro-meteorological profile, scintillometer, and infrared image data were collected over wet and dry bare soil, under clear and cloudy sky conditions. Initial evaluations indicate excellent agreement between the measured optical turbulence structure parameter and estimates of the parameter using measured energy fluxes of sensible and latent heat. Models of the radiation/energy balance components will be evaluated in future research. The results from this field test will be used to improve the knowledge base of meteorological processes within the surface boundary layer, radiation/energy balance partitioning, and atmospheric effects on optical turbulence and infrared imagery.

173

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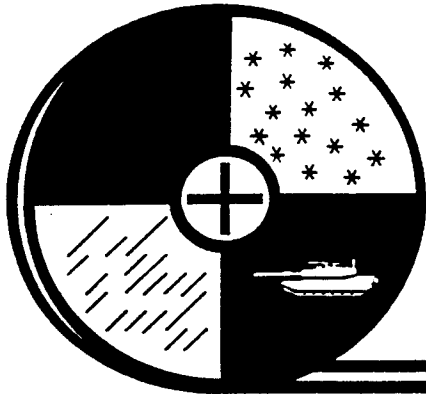U.S. Army Research Laboratory

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